Technical Note

Experiment 951: A3 Line Beam Window Evaluation

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Abstract

This technical note addresses the issues associated with the interaction of the Experiment-951 proton beam with the vacuum windows of the A3 line at AGS. Specifically, it summarizes the desired proton beam parameters, it describes the pulse structure and profile, and it outlines the reasoning for selecting the optimal location for the most critical window. Further, based on energy deposition calculations it evaluates the thermal response and the resulting thermal shock in the most critical window and estimates its safety margins.

INTRODUCTION

Requirement for conducting Experiment 951 for the Muon Collider project at AGS is the re-evaluation of the vacuum windows of the A3 line that brings the proton bunches to the experiment station. The need for a new safety analysis is due to the proton beam parameters of the experiment. Specifically, the experiment station would like to see 15 TP per bunch at energies of 24 GeV with a very short pulse width and a beam spot at the target location of 1 mm rms sigma or less. Such requirements make the selection of beam windows very challenging in that the thermal shock and fatigue induced by the beam-window interaction can exceed the safe limits of the selected material.

In this re-evaluation exercise the beam profile and the location of the vacuum windows along the A3 line were identified. Based on the smallest beam profile that can be observed during either normal operations or an off-normal condition, such as failure of a magnet or beam mis-focusing, the most critical section was identified. Based on such information from the beam optics, an optimal location for the most critical window was established and a safety analysis was performed.

As it will be shown in the sections that follow, a significant safety margin in all the A3 line windows exists including the last aluminum beam window which sees the smallest beam spot. It will be shown that in order to achieve safety in the last window a location upstream of the current end-of-vacuum line was selected.

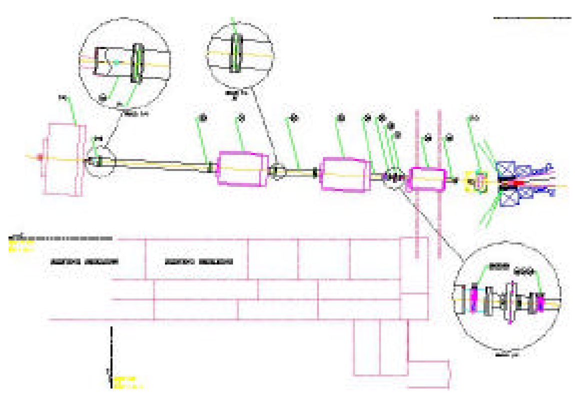
A3 Line and Target Location

Shown in Figure 1 are the details of the A3 line near the experimental station 951. Transitions of the beam line aperture take place between quads Q7 and Q8 (shown as items 23 and 29 respectively). Specifically, the 8-inch diameter beam pipe transitions to a 6-inch diameter section that includes a current transformer which in turn transitions to a 3-inch diameter beam pipe before the last quad (Q8). The selection of the location of the last vacuum window is based on the beam parameters and in particular on the beam spot profile in the shown section. Figures 2a and 2b depict the 3-sigma of the Gaussian beam in the A3 line.

Based on the beam profile, location 29 (past the last quad) has been eliminated as the place for the last vacuum beam window. The beam in that location has an rms sigma of 1 mm. As shown in this technical note, an aluminum beam window (material of choice at AGS lines) will be subjected to thermal shock stresses that exceed the safe limits of the material. An alternative location for the last A3 line window is the section between quads Q7 and Q8 where the beam spot size is much larger and thus the energy deposition density much smaller. Therefore, the beam will go through the last quad not in vacuum but in air.

Based on energy deposition calculations, thermal shock analysis and ease of installation, the location of transition between the 6-inch to 3-inch beam tube has been specified for the last vacuum window.

The rest of the aluminum windows upstream will experience, based on the beam profile of Figure 2, even less severe load than that of the last window. Thus, by ensuring safety in the most critical location, the safety of beam windows at all other locations is assured.



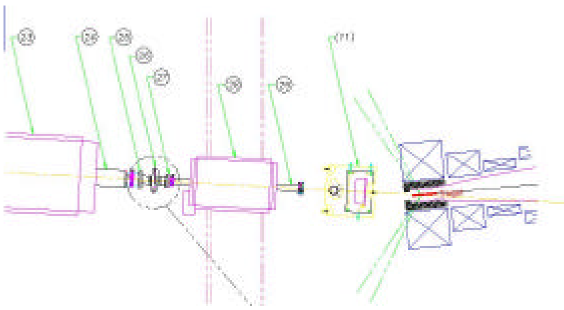


Figure 1. A3 line before Experiment Station 951

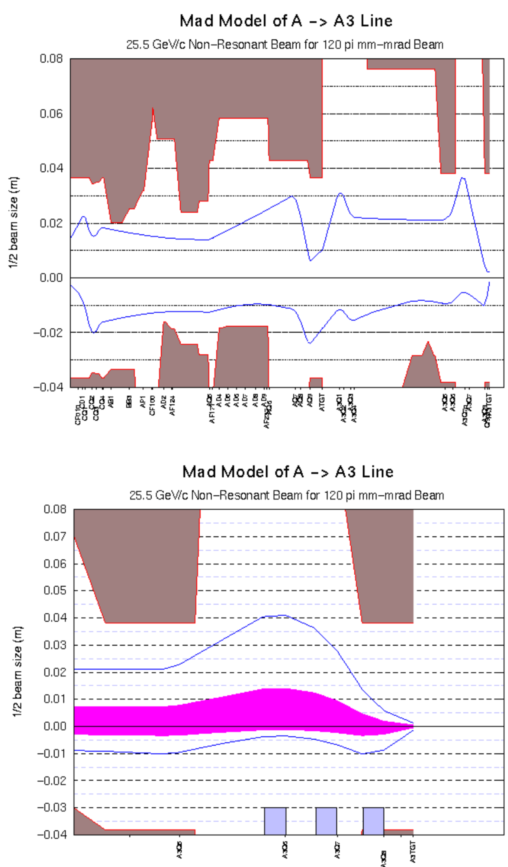


Figure 2. Depiction of the 3-sigma beam profile in the A3 Line of AGS. Shaded is the 1-sigma of the beam .

Pulse structure in space and time

In evaluating the thermal response of the window structures, the energy deposited in the material per incident 24 GeV proton was calculated using neutronics codes (MARS). While a Gaussian beam profile has been assumed for the spatial deposition, in the time space a triangular profile of the pulsed has been incorporated into the subsequent analyses. Such time-space profile is derived from previous experience at AGS where proton pulses exhibit the structure shown in Figure 3. The length of typical pulses at the base is of the order of 100 nsecs.

Figure 4 depicts the spatial profile of the spot size within 1 sigma at the location of the last vacuum window. The rms sigma of the beam in both planes at the selected location is 5.3 mm and 3.7 mm respectively.

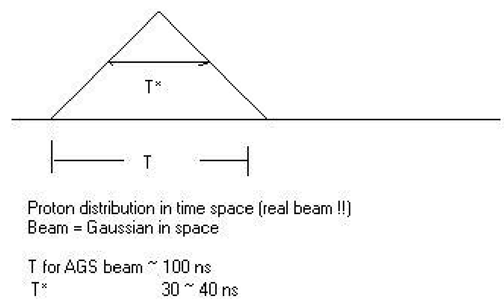


Figure 3. Pulse structure in time space

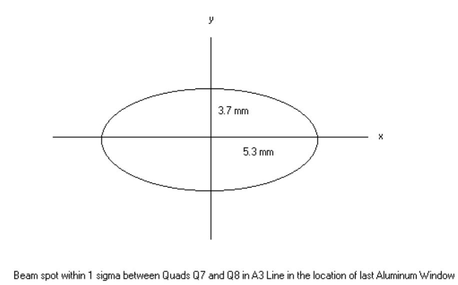


Figure 4. Beam profile of 1 rms sigma at last window location

Energy deposition before last quad Q8

The energy deposited (Joules/gram) in an aluminum window by the 24 GeV proton beam with the profile of Figure 4 and normalized to 15 TP per pulse is shown in Table 1. The calculation has been performed for window thickness up to 0.06 cm (24-mil).

Table 1. Energy deposition in aluminum window at location between last two quads of the A3 line

Energy deposition in Joules/gram in Aluminum window
Beam = 15 TP @ 24 GeV
rms Sigma_x = 5.3 mm
rms Sigma_y = 3.7 mm

z [cm]	r ---> [dr = 0.1 cm]									
0.001	4.32	4.39	3.86	3.34	2.59	1.92	1.41	1.00	0.69	0.46
0.003	5.04	4.70	3.70	3.50	2.76	2.04	1.57	1.16	0.76	0.48
0.005	4.82	4.44	3.91	3.34	2.74	2.03	1.55	1.07	0.65	0.47
0.007	4.46	4.46	3.74	3.41	2.66	2.02	1.60	1.06	0.74	0.45
0.009	3.77	4.58	3.89	3.24	2.66	1.99	1.65	1.09	0.71	0.51
0.011	4.63	4.75	4.13	3.43	2.62	2.15	1.54	1.16	0.74	0.49
0.013	4.20	3.86	3.89	3.53	2.81	2.25	1.58	1.07	0.71	0.48
0.015	4.34	4.78	4.06	3.34	2.59	2.08	1.50	1.11	0.80	0.46
0.017	4.39	4.61	3.86	3.50	2.71	2.14	1.54	1.15	0.82	0.48
0.019	5.54	4.03	4.27	3.38	2.69	2.12	1.55	1.06	0.75	0.48
0.021	4.56	4.30	3.86	3.34	2.88	2.15	1.59	1.08	0.79	0.49
0.023	5.33	4.34	3.86	3.43	2.74	2.16	1.51	1.11	0.81	0.53
0.025	4.85	4.15	3.91	3.36	2.66	2.24	1.43	1.03	0.75	0.53
0.027	5.38	4.56	4.18	3.48	2.71	2.14	1.51	1.03	0.82	0.45
0.029	4.61	4.46	3.82	3.34	2.64	2.16	1.64	1.01	0.82	0.44
0.031	5.42	4.51	4.30	3.65	2.83	2.22	1.69	1.11	0.73	0.48
0.033	4.90	4.54	4.32	3.48	2.78	2.36	1.54	1.10	0.79	0.54
0.035	5.02	4.20	4.18	3.38	2.86	2.09	1.57	1.04	0.74	0.47
0.037	4.20	4.39	4.25	3.62	2.71	2.04	1.60	1.08	0.77	0.46
0.039	4.97	4.30	4.06	3.12	2.90	2.06	1.65	1.06	0.78	0.44
0.041	5.33	3.98	4.03	3.36	2.90	2.22	1.49	1.04	0.76	0.48
0.043	4.37	4.68	3.84	3.38	2.76	2.06	1.65	1.09	0.79	0.49
0.045	5.21	4.44	3.94	3.38	2.42	2.04	1.58	1.08	0.72	0.51
0.047	4.61	4.85	3.89	3.55	2.88	2.11	1.52	1.26	0.72	0.47
0.049	5.90	4.27	4.08	3.43	2.62	1.99	1.49	1.07	0.83	0.45
0.051	4.82	4.18	4.13	3.62	2.88	2.24	1.55	1.09	0.73	0.45
0.053	4.51	4.08	4.08	3.46	2.71	2.15	1.48	1.03	0.79	0.48
0.055	4.20	4.30	3.91	3.34	2.52	2.07	1.57	1.11	0.74	0.54
0.057	4.97	4.51	3.65	3.43	2.66	2.07	1.50	1.10	0.72	0.55
0.059	4.80	4.39	3.84	3.22	2.76	2.04	1.48	1.03	0.70	0.46

Thermal Response

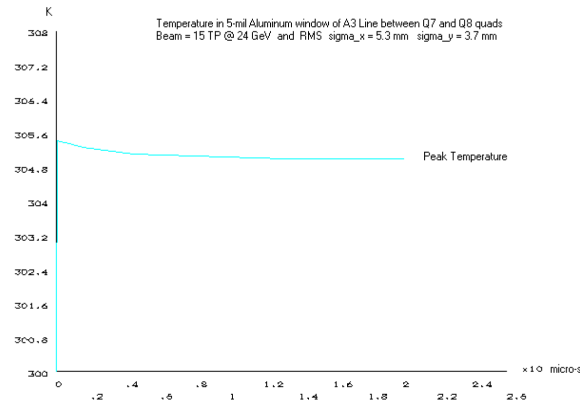
The vacuum window at the end of the A3 line will be 5-mil thick and made of 303 Aluminum alloy. The thickness selection complies with the AGS engineering rule that requires about 1.5-mil of thickness per inch of diameter. Given that the beam diameter window at the selected location is 3 inches, the 5-mil thickness of available material will suffice.

The thermal analysis of the window interacting with the nominal beam was performed using finite element analysis with the code ANSYS. The energy deposition from Table 1, up to the specified thickness of 5-mil, was input into the model along with the physical properties of aluminum in a transient analysis that satisfied the time structure of the pulse shown in Figure 3.

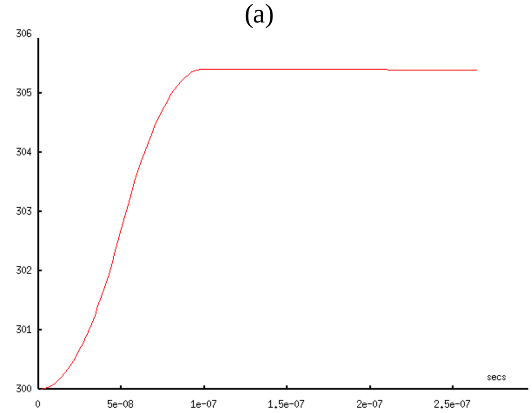
Figure 5a & 5b depict the development of the peak temperature in the aluminum window. The maximum temperature rise in the window is less than 6 degrees C per pulse. Given that under normal operations the experiment will receive pulses at great time distances apart, the temperature rise in the material as a result of subsequent pulses will be minimized. In the worst case scenario when all six micro-pulses in the ring totaling 60 TP and spaced by 33 ms are sent to the experiment, the temperature rise in the window will be approximately 24 degrees C.

Thermal Shock Stress Analysis

The safety evaluation of the window structure is based on the resulting quasi-static and, subsequently, shock stresses that develop in the material due to the rapid heating.



(a)



(b)

Figure 5. Temperature rise in the aluminum window due to the energy deposition of Table 1. Fig. 5a shows the temperature rise with relaxation and Fig. 5b depicts just the rise part resulting from the triangular pulse shape.

Quasi-static stresses are the initial stresses that develop purely due to temperature rise and the inability of the affected material to expand and relieve the loading. While approximations for thin structures are used to estimate the initial stresses, the nature of the stress within the material, no matter how thin, is three-dimensional. The directional stress is defined by

$$\sigma = E \quad / 1 - 2 \quad \text{(3-D)}$$
$$\sigma = E \quad / 1 - \quad \text{(2-D)}$$

where, the Poisson's ratio. Of interest, however, is the equivalent stress or Von-Mises stress that develops indicating the deviation from hydrostatic state of stress that results due to temperature rise. In the case of instant temperature rise, the quasi-static stress that develops is in most cases the upper limit of stress. In the realistic case of temperature rise as shown in Figure 5, the length of the pulse as well as the thickness of the window are critical parameters. In such case the dynamic processes, and thus the stress waves, are initiated while the temperature in the heated zone is building up.

Shown in Figure 6 is the temporal variation of the equivalent stress in the mid-thickness of the 5-mil aluminum window. Clearly visible is the ringing that occurs as a result of through-thickness stresses traveling between the two surfaces of the window with period

$$= 2\ h/c$$

where h is the window thickness and c is the sonic velocity in the material (~ 6350 m/sec in aluminum).

The second peak represents the stress wave reflected by the boundary of the window when it arrives at the center. As seen from the amplitude of the peak, geometric attenuation of the wave has occurred. The build-up of stress due to converging waves at the center is not observed in a partially heated window. Further, the dynamic finite element analysis has precisely captured the times of stress wave travel and arrival.

Figures 7a & 7b depict the radial stress wave at the center of the heated zone as well as at mid-distance to the window edge.

The peak equivalent stresses of about 15 MPa that result from a single pulse are quite insignificant as compared with the limits of the aluminum alloy window material with S_yield = 255 MPa and S_ult = 290 MPa.

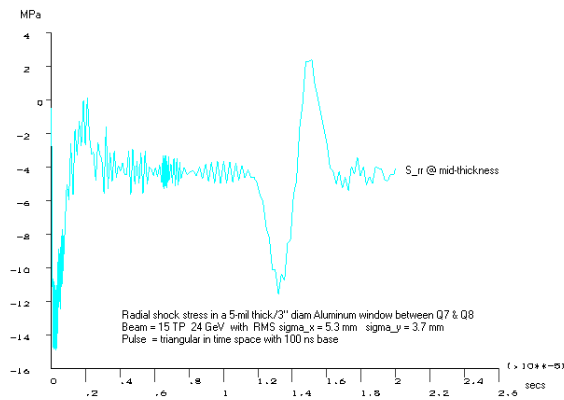


Figure 6. Radial stress in the 5-mil aluminum window.

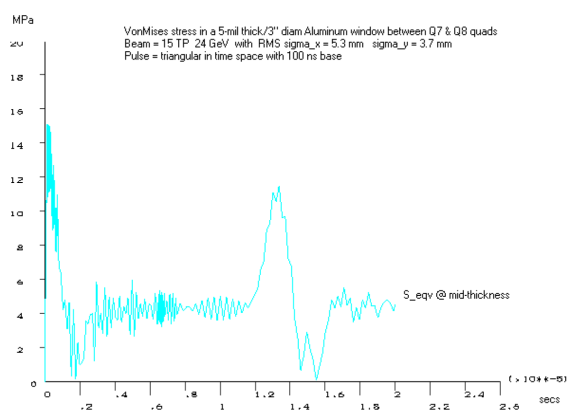


Figure 7. Equivalent (VonMises) shock stress in the 5-mil Aluminum window due to energy deposition in Table 1.

Thermal Shock of an Aluminum Window past the last Quad of the A3 Beam Line

In this section the thermal shock analysis of the last vacuum window in the A3 line is presented when placed after the last quad (Q8) and before the experiment station. Based on the beam profile in this location (from Figure 2) the beam spot is approximately round with an rms sigma of approximately 1mm.
Table 1 lists the energy deposition in such location for the same beam parameters (15 TP per-pulse at 24 GeV). The energy density within one sigma is almost 20 times higher. That results in a temperature rise of approximately 110 degrees C within 100 ns (Figure 8).

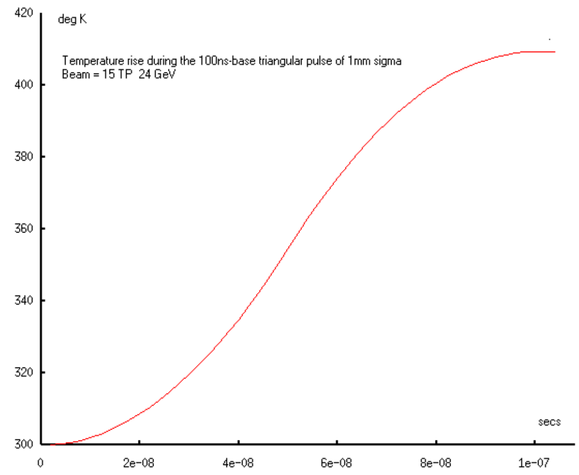


Figure 8. Temperature rise in aluminum due to 1mm rms sigma beam

Table 2 Energy deposition in aluminum window past the last quad of the A3 line

ENERGY DEPOSITION IN ALUMINUM WINDOW [joules/gram]
Beam = 16 TP 24 GeV with 1mm rms sigma

z [cm]	r ----> [dr = 0.5 mm]									
0.001	91.20	61.92	39.36	20.83	6.70	1.93	0.42	0.10	0.02	0.01
0.003	78.00	71.28	38.16	19.82	6.82	1.92	0.36	0.08	0.01	0.01
0.005	101.76	69.12	43.68	19.94	7.20	2.07	0.41	0.09	0.01	0.02
0.007	89.04	75.60	45.36	21.02	6.22	2.38	1.44	0.36	0.02	0.02
0.009	81.36	67.20	44.40	20.47	6.91	2.34	0.37	0.08	0.04	0.01
0.011	98.40	75.12	39.84	20.45	7.75	2.81	0.38	0.09	0.02	0.00
0.013	76.56	67.68	42.00	21.58	7.90	1.97	0.38	0.39	0.02	0.01
0.015	96.24	64.80	38.64	20.57	7.39	2.04	0.69	0.08	0.01	0.01
0.017	76.08	63.12	41.28	17.62	8.33	1.58	0.73	0.08	0.02	0.02
0.019	79.92	59.04	45.60	20.76	8.28	2.45	0.77	0.09	0.02	0.01
0.021	87.36	68.64	43.20	19.66	7.20	2.10	0.41	0.38	0.03	0.02
0.023	102.96	70.08	42.72	23.28	7.27	2.54	0.43	0.08	0.03	0.03
0.025	79.68	69.60	41.76	17.50	7.30	2.52	0.42	0.08	0.01	0.01
0.027	84.24	63.12	39.84	21.79	6.36	1.68	0.77	0.39	0.02	0.01
0.029	95.76	83.28	44.16	17.86	7.49	1.57	1.46	0.08	0.03	0.01
0.031	76.56	64.32	43.20	18.94	7.49	2.47	0.71	0.08	0.03	0.04
0.033	123.36	79.68	37.92	16.44	9.38	2.02	0.40	0.07	0.01	0.01
0.035	97.20	66.48	37.44	24.96	8.57	1.58	0.39	0.38	0.02	0.00
0.037	85.68	60.96	39.60	22.49	8.54	2.52	0.35	0.07	0.01	0.00
0.039	88.08	70.08	40.32	24.96	6.41	1.66	0.72	0.08	0.01	0.01
0.041	76.08	68.16	39.36	18.94	7.56	2.52	0.36	0.38	0.03	0.00
0.043	80.16	64.56	42.48	19.73	8.50	4.10	0.41	0.07	0.02	0.01
0.045	89.04	62.64	45.36	20.76	6.46	1.58	0.38	0.07	0.01	0.01
0.047	88.08	69.60	43.92	22.03	7.32	2.04	0.42	0.08	0.01	0.01
0.049	70.32	79.20	36.96	19.46	8.33	1.97	0.39	0.10	0.02	0.00
0.051	82.80	74.16	42.96	19.27	6.86	2.74	1.43	0.11	0.02	0.01
0.053	70.08	76.56	41.52	19.58	7.54	2.04	0.39	0.14	0.02	0.01
0.055	79.20	70.08	40.80	17.30	7.54	3.19	0.39	0.09	0.03	0.01
0.057	100.56	62.64	40.08	16.18	6.89	1.98	0.72	0.10	0.03	0.01
0.059	75.12	65.52	44.16	21.65	6.74	1.46	0.35	0.39	0.03	0.01

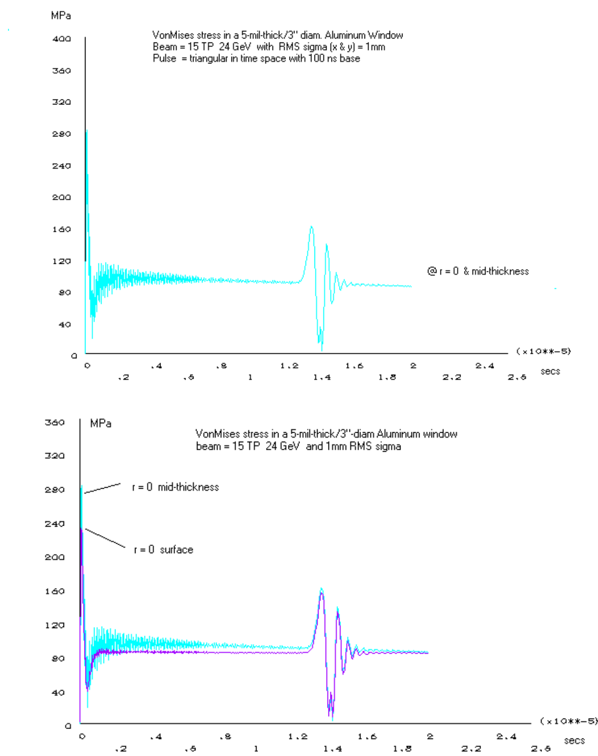


Figure 9. Shock stress (Von-Mises) in a 5-mil aluminum window from 1mm rms sigma beam

The resulting quasi-static and shock stresses in the aluminum window placed in such location with a 1 mm rms sigma proton beam going through it are approaching the ultimate strength limits of the material. It is seen in Figure 9 that the peak Von-Mises stress due to a 15 TP pulse exceeds 280 MPa, which represents the ultimate strength of the aluminum alloy available for window material at AGS.
Shown in Figures 11 and 12 are the shock stresses that will result in a similar aluminum window from a 15 TP square pulse 34 ns long (instead of triangular with 100 ns base). It is seen that the resulting shock stresses increase as a result of the shorter pulse length.

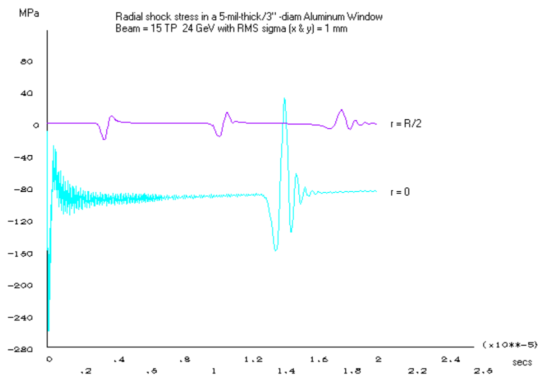


Figure 10. Radial shock stress in a 5-mil thick aluminum window induced by proton beam after the last quad of A3 line

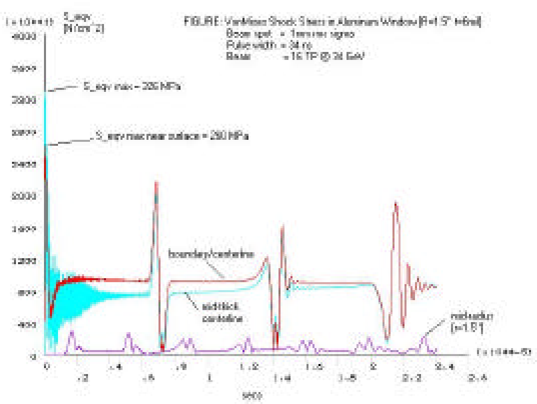


Figure 11. Von-Mises stress in aluminum window induced by a 34-ns square pulse and 1mm rms sigma

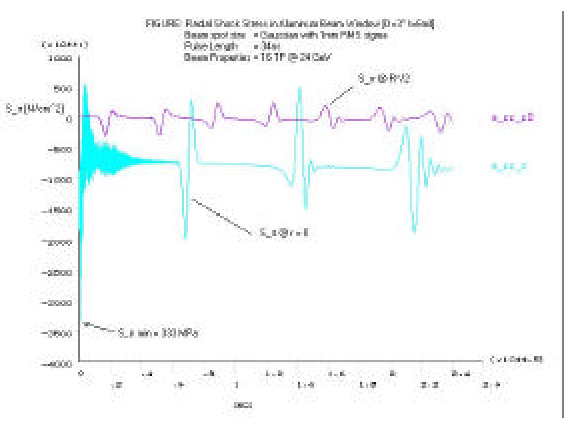


Figure 12. Radial shock stress in aluminum window caused by a 34-ns square pulse and 1mm rms sigma beam

CONCLUDING REMARKS

Based on the results of the thermal shock analyses for the aluminum windows of the A3 line, which incorporate beam optics, energy deposition, thermal response and stress shock, it is evident that the safest location for the most critical window is in the section between the last two quads of the A3 beam line. Given that the primary concern is for the window structure to survive a single pulse of 15 TP, while maintaining a significant safety factor for vacuum, the chosen location and the window material satisfy such criterion. The thermal shock stress that is experienced per pulse is approximately 15 MPa, well below the safety limits of yield or ultimate strength of the material (250 MPa and 290 MPa respectively). Even under the worst case scenario where all 60 TP in the train of micro-pulses are directed toward the experiment, the resulting shock stress conditions stay well below the acceptable safety limits.

Having satisfied the operational safety of the last and most critical of windows in the A3 line, it is concluded that all upstream windows, which interact with a beam spot that is larger than that of the critical section, will have even larger safety margins. Therefore, there is no concern of failure during normal or off-normal operations of any aluminum vacuum windows in the A3 line.

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